

## **Wave dissipation and balance - NOPP wave project**

Fabrice Ardhuin

Ifremer

Laboratoire d'Océanographie Spatiale

Plouzané, FRANCE 29200

phone: (+33) 298-224915 fax: (+33) 298-224533 email: [ardhuin@ifremer.fr](mailto:ardhuin@ifremer.fr)

Award Number: N00014-10-1-0383

<http://wwz.ifremer.fr/iowaga>

### **LONG-TERM GOALS**

Wind-generated waves play a prominent role at the interfaces of the ocean with the atmosphere, land and solid Earth. Waves also define in many ways the appearance of the ocean seen by remote-sensing instruments. Beyond these geophysical aspects, waves also affect human activities at sea and on the coast. The long-term goals of this research are to obtain a better understanding of the physical processes that affect ocean surface waves and their interactions with ocean currents and turbulence, the atmosphere, seismic waves, sediments and remote sensing systems, and to improve our forecasting and hindcasting capacity of these phenomena from the global ocean to the nearshore scale.

### **OBJECTIVES**

- Observe and parameterize the dissipation of ocean waves due to breaking, wind-wave interactions, or bottom friction
- Advance spectral wave modeling at all (global to beach) scales in a unified framework, in terms of parameterization and numerical developments
- Help the application of wave models to new problems (upper ocean mixing and surface drift, use of seismic noise data, air-sea gas exchange ...) and use these applications for feedback on the wave model quality

### **APPROACH**

By combining theoretical advances with numerical models, remote sensing and field observations, we investigate the physical processes that affect wind-generated ocean gravity waves. The various dissipative processes that contribute to the spectral wave evolution are isolated by considering geophysical situations in which they are dominant: the long-distance swell propagation in the case of air-sea friction, the evolution of swells on shallow continent shelves in the case of bottom friction, the energy level in the spectral tail in the case of cumulative breaking effects, and the breaking statistics of waves. These require the acquisition of new data using stereo-video techniques, for the spectral levels

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>30 SEP 2013</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2013 to 00-00-2013</b>	
4. TITLE AND SUBTITLE <b>Wave dissipation and balance -NOPP wave project</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Ifremer (French Research Institute for Exploitation of the Sea),Laboratory Space Oceanography,Plouzane, France 29200,</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES					
14. ABSTRACT					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>8</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

of waves of 1 to 10 m wavelength, and the statistics of whitecaps. The full model is then confronted to a wide range of observations starting from global altimeter, SAR and buoy data. Alvise Benetazzo (ISMAR Venezia) is performing the calibration of the stereo system and the reconstruction of sea surface geometries, that expertise has been transferred to Ifremer with graduate student Fabien Leckler and developments at the two institutions are now allowing reliable analysis of data acquired in 2011. The spectral analysis and whitecap detection is performed at Ifremer, under the supervision of Fabrice Ardhuin. All the wave modeling effort at Ifremer (theory, parameterization and calibration) is performed by Fabrice Ardhuin and Fabien Leckler.

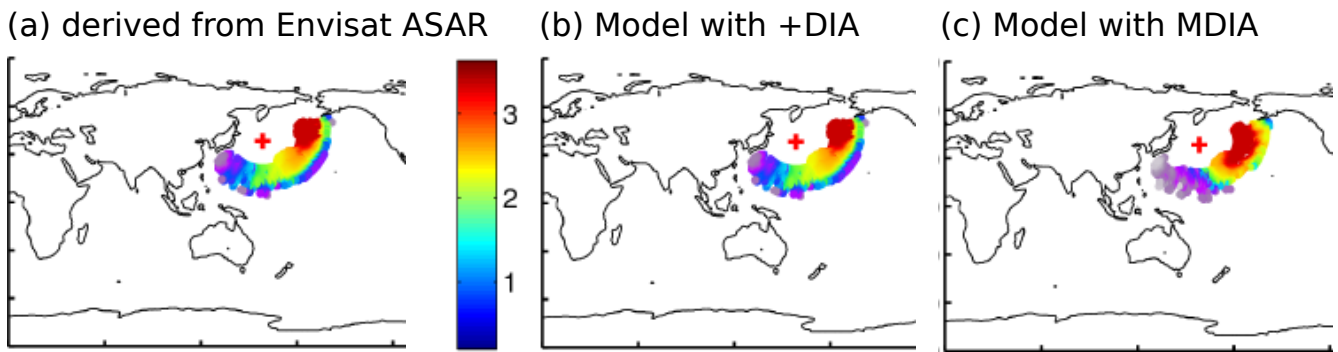
## WORK COMPLETED

**Wave model parameterizations for wind wave evolution** The main challenge faced for the energy balance of wind seas is the non-local nature of all terms in the spectral domain. This is well known for the non-linear 4-wave interaction term (Hasselmann, 1962), but it is becoming also increasingly clear for the wind input and the dissipation terms. For the wind input, the well-known quasi-linear effect (Fabrikant, 1976; Janssen, 1991) is a positive feedback of the short waves in the spectrum on the growth of all spectral components, whereas the sheltering effect discussed by Hara and Belcher (2004), is a negative feedback term that affects the short wave growth based on the long wave growth. The combination of the two effects leads to behaviors that are not fully understood, with clear impacts on the variability of wind stress and mean square slopes.

Similarly, there is growing evidence for the generation of both longer and shorter wave components from the breaking of waves of intermediate scale (Yurovskaya et al., 2008; Tulin and Waseda, 1999; Caudal, 2012), in addition to the “cumulative” effect of short wave dissipation due to large scale breakers, already introduced in source term parameterizations (Banner and Morison, 2010; Ardhuin et al., 2010; Rogers et al., 2010). On top of that, it is also expected that the breaking of waves changes the wind profile and wind-wave growth term (Reul et al., 2008), an effect introduced in the parameterization by Banner and Morison (2010).

Finally, it is well known that the DIA parameterization for non-linear interactions leads to biases in spectral shape and integrated parameters (Banner and Young, 1994; Ardhuin et al., 2007). Using a very preliminary test of the multiple-DIA from (?), Rollet (2013) showed how important the directional spreading was for far-field swells from a storm. Indeed the settings of the MDIA tuned to the Tolman and Chalikov parameterization produced pathologically narrow directional spectra when applied with the TEST451 parameterization from Rascle and Ardhuin (2013). This was a good candidate to reveal that the shape of the swell fields in extra tropical storms is strongly influenced by the directional spreading of the spectra within the storm, with different results given by different parameterizations. This is illustrated in figure 1. Future work with MDIA will require a tuning of the interaction coefficients.

There are thus many effects that need to be considered, with strong non-linear interactions between them, and it is not clear how to transform each type of measurement into a clear constraint for the functional form and magnitude of these effects. We have begun to test several aspects and there is not clear positive trade off when adding more effects into the TEST451 parameterization (?). This work has been partly delayed due to the difficulty of hiring personnel at Ifremer in FY2013. This line of investigation will be continued.



**Figure 1:** *Observed and modelled maps of significant swell height, one day after propagation of swell from April 3, 2009, in the North Pacific. The MDIA parameterization of 4-wave interactions is used with the settings adjusted to the Tolman and Chalikov wind-wave growth and dissipation and should be retuned for the TEST451 parameterization used here. Picture adapted from Rollet (2013).*

**Bottom friction and coastal model numerics** Bottom friction: The parameterization by Ardhuin et al. (2003) based on data of the 1999 SHOaling Waves EXperiment (SHOWEX) has been thoroughly tested for the North Carolina shelf and French Atlantic coast. Adjustements included the setting of maximum roughness values for rock bottoms.

**Hindcasts and wind speed adjustments** The time-varying biases in ECMWF operational analyses and CFSR hindcasts require some specific adjustments of model parameters. For recent years, the higher level of wind speed percentiles above 80 require a specific reduction in wind speed for the years 2007 to 2012. We have thus corrected our hindcasts for these years with a reduced BETAMAX parameter from 1.33 to 1.15. Similarly, the value used with ECMWF operational analyses was reduced from 1.52 for 2009 to 1.45 for the year 2011, and further reductions are expected with the increase in resolution of the model and change of WAM model parameterization.

### Data analysis

Acoustic noise: Ardhuin et al. (2013) have used the variability of ocean bottom noise records at frequencies below 1 Hz to validate the changing directional properties of ocean waves as modeled with different source term parameterizations. Stereo-video data: The quality of 3D reconstructions is now well established as discussed in Fedele et al. (2013) based on data acquired in 2009. Recordings from the 2011 experiment in Katsiveli (Black Sea), have finally been processed to a satisfactory degree of quality, thanks ot to the contribution from Alvis Benetazzo who developed a self-calibration procedure that allowed to correct the viewing angles of cameras.

### Implementation in WAVEWATCH III

Several items have made their way to the trunk of the NCEP subversion server over FY2013

- an upgrade of the multi-grid system allowing two-way nesting between regular grids and triangle-based meshes.
- an interface to the IOS tidal analysis software, allowing water levels and currents to be defined from tidal constituents.
- estimation of whitecap coverage and foam thickness from the dissipation parameterization as described in Leckler et al. (2013)

While others are still being tested:

- a data assimilation procedure based on SAR-derived swell fields.
- The Eldeberky and Battjes triad parameterization
- a parametric source of free infragravity wave energy at the shorelines.
- an evolution of wind wave generation and dissipation, taking into account modulation effects and short wave generation by breaking waves.

## RESULTS

Most of the development work this year has focused on coastal applications, in particular with numerical aspects associated to unstructured grid, for which the WAVEWATCH III implementation has proven very robust, and calibration work on bottom friction. This follows previous works on the effects of currents, described in ?. **Bottom friction.** Using the adjusted SHOWEX bottom friction (Ardhuin et al., 2003), a 20-year hindcast of coastal sea states around France, using tidal currents and elevations, and a map of sediment types. Roland and Ardhuin (tted) have shown that this is the most accurate hindcast produced so far for that region, and the variability of bottom types does correspond to different wave attenuation patterns recorded by buoys. This is illustrated in figure 2.

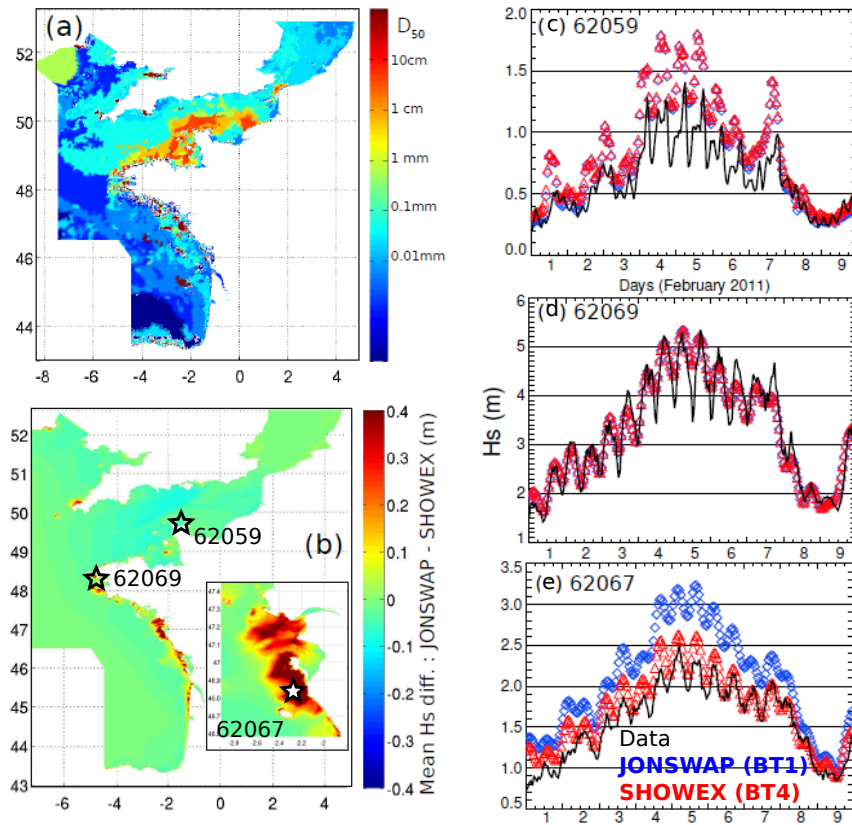
**Underwater acoustics** Another area of activity was the application of numerical wave models to the analysis of underwater sound at frequencies below 1 Hz. Ardhuin et al. (2013) showed that the latest parameterization by Rascle and Ardhuin (2013) was particularly well suited to reproduce the variability of the acoustic noise level induced by the directional wave distribution, at acoustic frequencies up to 0.8 Hz in the case of data recorded north of Hawaii. At higher frequencies, the model misses the dynamics of the recorded signal, pointing to the missing impact of wave breaking on the wave spectrum, as already suggested by Duennebier et al. (2012), and consistent with radar backscatter studies (Yurovskaya et al., 2008).

## IMPACT AND APPLICATIONS

The combined use of underwater acoustic data and numerical wave models offers new opportunities for investigating the directional wave spectrum, up to very high frequencies. We are aware of the work done in San Diego by W. Farrell and W. Munk on this topic and have started exchanging ideas about it. W. Farrell's early comments on our acoustic noise modeling paper by Ardhuin et al. (2013) was essential for resolving discrepancies in previous analyses. We are currently processing the 2011 Katsiveli data to reveal the shape of 1 to 5 m wavelength waves, without directional ambiguity, in connection with that particular acoustic work.

**National Security** Improving wave forecasts are relevant to a variety of defence applications. The most dramatic improvement brought in the operational models by the present work is an improved representation of swells which are most relevant for amphibious operations.

**Quality of Life** The transport of contaminants in the nearshore ocean is largely driven by waves. The capability and understanding of this driving process in three dimensions will certainly lead to improved water quality models.



**Figure 2:** (a) Map of sediment median diameter and (b) mean difference in significant wave height (in meters) over the month of February 2010 between a model run using the 'JON- SWAP' bottom friction parameterization and another using the 'SHOWEX' parameterization with a constant Nikuradse roughness length of 12 cm for rocks. Inset is a zoom on the region around Yeu and Noirmoutier islands where the impact of this friction is very clear. (c)-(e), Time series of observed and modeled significant wave height at several buoys using the JONSWAP (blue diamonds) or SHOWEX (red triangles) parameterizations for bottom friction, compared to hourly buoy measurements (solid line). The location of these buoys is indicated by stars in (b). Figure adapted from Roland and Ardhuin (tted).

## TRANSITIONS

As mentioned above, operational wave models at NOAA/NCEP have been switched from the parameterization by Tolman and Chalikov (1996) to the TEST451, only 3 months after the parameterization had been adjusted. This shows the amazing capability brought about by the new way of developing model frameworks at NCEP using outside contributions on the same subversion server. This happened during FY2012. Since that time, many adjustments and bug corrections have been disseminated, using the same tools, and have made their way into the version 4.12 of the WAVEWATCH III code, now publically available on request from NCEP. We will continue helping NOAA/NCEP and others in testing and implementing these parameterizations. We are also committed to support outside users, with a training course in Brest, France, which is open to all interested parties, in coordination with the University of Maryland and NCEP efforts. The first training will take place on the week of November 4, 2013 and participants from all over the world will attend, including people from

Deltares (NL), and U.S. universities. A second edition is scheduled for March 2014.

## RELATED PROJECTS

The present “Ocean Waves Dissipation and spectral Balance” (WAVE-DB) shares many of the objectives of the the Integrated Ocean Waves for Geophysical and other Applications (IOWAGA) project, funded by the European Research Council. As a result, results from both projects are reported on the same web pages, where the contribution from each is clearly identified. Whereas WAVE-DB is focused on the development of stereo-video techniques and numerical wave modeling, IOWAGA allows a broader perspective with work on remote sensing and seismic noise, which allow a more informed calibration of the numerical wave model. Finally, the WAVE-DB activity is also benefiting from the GLOBWAVE project, funded by the European Space Agency and the French Space Agency to facilitate the use of satellite remote sensing data of ocean waves.

## REFERENCES

- F. Ardhuin, W. C. O'Reilly, T. H. C. Herbers, and P. F. Jessen. Swell transformation across the continental shelf. part I: Attenuation and directional broadening. *J. Phys. Oceanogr.*, 33:1921–1939, 2003. URL <http://journals.ametsoc.org/doi/pdf/10.1175/1520-0485%282003%29033%3C1921%3A%20STATCS%3E2.0.CO%3B2>.
- F. Ardhuin, T. H. C. Herbers, K. P. Watts, G. P. van Vledder, R. Jensen, and H. Graber. Swell and slanting fetch effects on wind wave growth. *J. Phys. Oceanogr.*, 37(4):908–931, 2007. doi: 10.1175/JPO3039.1.
- F. Ardhuin, E. Rogers, A. Babanin, J.-F. Filipot, R. Magne, A. Roland, A. van der Westhuysen, P. Queffelec, J.-M. Lefevre, L. Aouf, and F. Collard. Semi-empirical dissipation source functions for wind-wave models: part I, definition, calibration and validation. *J. Phys. Oceanogr.*, 40(9):1917–1941, 2010.
- M. L. Banner and R. P. Morison. Refined source terms in wind wave models with explicit wave breaking prediction. part I: Model framework and validation against field data. *Ocean Modelling*, 33: 177–189, 2010. doi: 10.1016/j.ocemod.2010.01.002.
- M. L. Banner and I. R. Young. Modeling spectral dissipation in the evolution of wind waves. part I: assessment of existing model performance. *J. Phys. Oceanogr.*, 24(7):1550–1570, 1994. URL <http://ams.allenpress.com/archive/1520-0485/24/7/pdf/i1520-0485-24-7-1550.pdf>.
- G. V. Caudal. Imbalance of energy and momentum source terms of the sea wave transfer equation for fully developed seas. 8:1085–1098, 2012.
- F. K. Duennebie, R. Lukas, E.-M. Nosal, J. Aucan, and R. A. Weller. Wind, waves, and acoustic background levels at station ALOHA. *J. Geophys. Res.*, 117:C03017, 2012. doi: 10.1029/2011JC007267.
- A. L. Fabrikant. Quasilinear theory of wind-wave generation. *Izv. Atmos. Ocean. Phys.*, 12:524–526, 1976.



- T. Hara and S. E. Belcher. Wind profile and drag coefficient over mature ocean surface wave spectra. *J. Phys. Oceanogr.*, 34:3345–2358, 2004.
- K. Hasselmann. On the non-linear energy transfer in a gravity wave spectrum, part 1: general theory. *J. Fluid Mech.*, 12:481–501, 1962.
- P. A. E. M. Janssen. Quasi-linear theory of wind wave generation applied to wave forecasting. *J. Phys. Oceanogr.*, 21:1631–1642, 1991. URL <http://journals.ametsoc.org/doi/pdf/10.1175/1520-0485%281991%29021%3C1631%3AQLTOWW%3E2.0.CO%3B2>. See comments by D. Chalikov, *J. Phys. Oceanogr.* 1993, vol. 23 pp. 1597–1600.
- N. Rascle and F. Ardhuin. A global wave parameter database for geophysical applications. part 2: model validation with improved source term parameterization. *Ocean Modelling*, 70:174–188, 2013. doi: 10.1016/j.ocemod.2012.12.001.
- N. Reul, H. Branger, and J.-P. Giovanangeli. Air flow structure over short-gravity breaking water waves. *Boundary-Layer Meteorol.*, 126:477–705, 2008. doi: 10.1007/s10546-007-9240-3.
- W. E. Rogers, A. V. Babanin, and D. W. Wang. Observation-consistent input and whitecapping dissipation in a model for wind-generated surface waves: Description and simple calculations. *J. Atmos. Ocean Technol.*, 29(9):1329–1346, 2010.
- H. L. Tolman. A generalized multiple discrete interaction approximation for resonant four-wave interactions in wind wave models. *Ocean Modelling*, 70:11–24, 2013.
- H. L. Tolman and D. Chalikov. Source terms in a third-generation wind wave model. *J. Phys. Oceanogr.*, 26:2497–2518, 1996. URL <http://journals.ametsoc.org/doi/pdf/10.1175/1520-0485%281996%29026%3C2497%3ASTIATG%3E2.0.CO%3B2>.
- M. P. Tulin and T. Waseda. Laboratory observations of wave group evolution including breaking effects. *J. Fluid Mech.*, 378:197–232, 1999.
- M. V. Yurovskaya, V. A. Dulov, B. Chapron, and V. N. Kudryavtsev. Directional short wind wave spectra derived from the sea surface photography. *J. Geophys. Res.*, 113:C12024, 2008. doi: 10.1002/jgrc.20296.

## PUBLICATIONS

- Ardhuin, F., Dumas, F., Bennis, A.-C., Roland, A., Sentchev, A., Forget, P., Wolf, J., Girard, F., Osuna, P., and Benoit, M. (2012). Numerical wave modeling in conditions with strong currents: dissipation, refraction and relative wind. *J. Phys. Oceanogr.*, 42:2101–2120.
- Ardhuin, F., Lavanant, T., Obrebski, M., Marié, L., Royer, J.-Y., d’Eu, J.-F., Howe, B. M., Lukas, R., and Aucan, J. (2013). A numerical model for ocean ultra low frequency noise: wave-generated acoustic-gravity and Rayleigh modes. *J. Acoust. Soc. Amer.*, 133(10). in press.
- Fedele, F., Benetazzo, A., Gallego, G., Shih, P.-C., Yezzi, A., Barbariol, F., and Ardhuin, F. (2013). Space-time measurements of oceanic sea states. *Ocean Modelling*, 70:103–115.
- Leckler, F., Ardhuin, F., Filipot, J.-F., and Mironov, A. (2013). Dissipation source terms and whitecap statistics. *Ocean Modelling*, 70(9):62–74.



- Rascle, N. and Ardhuin, F. (2013). A global wave parameter database for geophysical applications. part 2: model validation with improved source term parameterization. *Ocean Modelling*, 70:174–188.
- Roland, A. and Ardhuin, F. (submitted). On the developments of spectral wave models: numerics and parameterizations for the coastal ocean. *Ocean Dynamics*, XX:XX.
- Rollet, M. (2013). Properties of swell fields. Master’s thesis, Ecole et Observatoire des Sciences de la Terre de l’Université de Strasbourg. in French.